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THESIS

COMPUTER AIDED DEFLECTION MEASUREMENT

OF AN AIRCRAFT WING

by

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This study produced a computer package capable of significantly enhancing the utility of the basic wing torsion/bending experiment through real-time data acquisition and analysis. Manual data acquisition required approximately ten minutes per static load, with additional time for data plotting and analysis. Computerized measurements are conducted in several seconds, and the data is automatically plotted on a dot-matrix printer. This improved system allows for expansion of the experiment to inlcude

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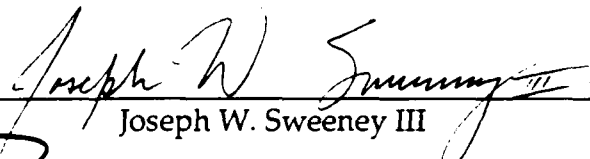B.S., United States Naval Academy, 1975

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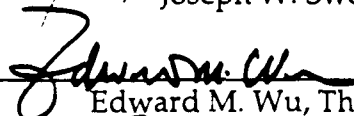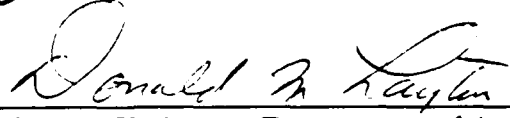
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ABSTRACT

The purpose of this study is to update the existing P-2V Wing Torsion/ Bending Structural Test to include computer-aided data acquisition and analysis. The system includes 20 displacement transducers, associated wiring and support framework, a dual DC voltage power supply, two Labmaster data acquisition expansion boards, an AT-compatible computer with 80286 processor and 80287 math co-processor, and ASYST software to perform all data processing.

This study produced a computer package capable of significantly enhancing the utility of the basic wing torsion/bending experiment through real-time data acquisition and analysis. Manual data acquisition required approximately ten minutes per static load, with additional time for data plotting and analysis. Computerized measurements are conducted in several seconds, and the data is automatically plotted on a dot-matrix printer. This improved system allows for expansion of the experiment to include testing a larger variety of static loading problems and the basic instrumentation to explore the wing's response to dynamic loading.

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ACKNOWLEDGEMENT

I. BACKGROUND

In the design concept of an aircraft by the manufacturer, many assumptions must be made concerning the actual performance characteristics of the final product - the aircraft itself. While many factors can be designed in or compensated for, the final physical verification tests must be made when the aircraft is actually produced. Prior to purchase of the aircraft either by an individual or the government, the manufacturer must conduct specific tests to ensure that the final product performs as predicted by design. While realizing that many tests will be conducted on every component of the aircraft, this thesis will address only the structural tests performed on the wing. These initial structural performance tests of the wing are referred to as "benchmark tests" in that they determine the wing's performance when new and provide a measuring point against which future tests can be compared after the aircraft has been in service.

While airborne, the aircraft's wing will be subjected to forces in all three axes: X, Y, and Z. These axes are depicted in Figure 1.1. Forces may be exerted on the
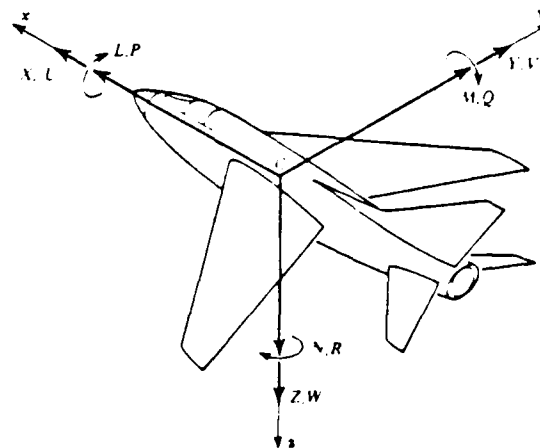
Figure 1.1 Aircraft Axis System (Etkin, p.10)

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wing in each of these axes, in a bending only mode, torque only, or a combination of these two modes. In flight, the wing would experience combined loads in all three axes, creating an extremely complex problem to model exactly in the laboratory. Despite these difficulties, the wing's performance can be characterized by basic bending, torsion, and bending/torsion structural testing. Through the principle of superposition, the wing's performance under complex loading may be predicted.

Once the aircraft has left the factory, and has been in service for some period of time, periodic maintenance checks will be performed on the wing to ensure continued structural integrity. These tests must be non-destructive in nature, preserving the wing , and should be able to be completed as expediently as possible in order to minimize the time the aircraft is not available for flying and fulfilling its assigned mission.

Two different modes of testing are available: static tests and dynamic tests. The static tests are performed by applying a load to the wing, holding it in that position, and taking the required measurements at prescribed positions, followed by incrementing the load and measurements. It should be noted that while the static test provides a good verification of the design, it does not provide a sensitive diagnosis of in-service local deterioration unless the measurements happen to be made in the close vicinity of the damage.

The dynamic modal analysis is potentially more sensitive to detect and identify local damages. The dynamic tests could be conducted in two different ways:

1. Apply a load to the wing. Release the load, and observe the resulting oscillations. This method allows measurement of the transient or impulse response, but provides little information concerning the natural frequency of the wing.

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2. Using a large oscillator, force the wing to oscillate at a given frequency and compare the output characteristics to the inputs. This second method allows for more extensive tests, since performance at or near any harmonics of the natural frequencies of the wing can be measured.

Structural responses of an aircraft wing are determined by the following governing equations:

$$\partial_i \sigma_{ij} + X_j = 0 \tag{1}$$

$$\sigma_{ij} = c_{ijkl} \varepsilon_{kl} \tag{2}$$

$$\varepsilon_{ij} = \frac{1}{2} \left\{ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right\} \tag{3}$$

The structural response of a wing can be measured in terms of strains or in terms of displacements. In the strain approach, strain components (ε_{ij}) are measured utilizing strain gauges; with substitution of the strain measurements into the constitutive relations (Eq. 2), the stresses can be evaluated. Through the equilibrium equations (1), the stress resultants can be compared to the actual applied forces and moments. Computation of the strain measurements has been completed by LCDR J.J. Miller (1986). The deflection (displacement) of the wing can be obtained from the strain measurement by solving the partial differential equations of strain-displacement (Eq. 3).

In the displacement approach, the displacement components U are measured at various points of the wing. In contrast to the previous approach, the strain components may be measured by differentiating the strain-displacement equations (Eq. 3). The strain components can in turn be used to determine the stresses σ (Eq. 2) and ultimately relate to the external forces and moments via the

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equilibrium equations (1). This thesis will deal with the computerization of the wing deflection measurements.

To demonstrate testing principles and procedures, the Aeronautical Engineering Department procured the outboard section of a P-2V wing from the storage yard at Davis-Monthan Air Force Base in the mid-1950's. The outboard section of the wing is that portion from outboard of the engine mount to the wingtip. The leading edge devices and flaps and associated equipment have been removed from the wing to allow analysis of the performance of the basic wing structure, unencumbered by the extraneous equipment normally present. The wing has been mounted in an inverted position to facilitate demonstration of aerodynamic in-flight forces by using distribution of sandbags hung from the wing. This particular wing has been overstressed, which demonstrates that irregularities can be diagnosed in a wing which has deteriorated in service.

Since the Aeronautical Engineering Department is not set up solely for the manufacture and structural testing of aircraft, the P-2V wing mounted in Halligan Hall is only configured for testing in the Z-dimension by concentrated forces and moments. This arrangement fulfills the objective of demonstrating testing methods and the practical aspects of structural analysis to the students. The current set-up allows for bending, torsion, and combined bending/torsion at the tip of the wing. Demonstration of aerodynamic pressure by distributed weights is another aspect of testing for future addition.

In the past, while strain measurements were measured and computed by computerized methods, measurement of the wing deflection still required the use of a surveyor's theodolite to measure wing deflections. The deflection at each wing station was determined by comparing a tare reading to a subsequent reading taken while the wing was subjected to a load. At the start of the experiment, one operator sighted each ruler through the theodolite, calling out readings to be recorded by a second operator. This established the tare readings. A load was then

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applied to the wing, and another set of readings was called to the recording operator. The two sets of readings were then compared to determine the change in position of the wing at each station. While this method was simple in principle and relatively easy to execute, it was also time consuming, not interactive (i.e. results are not known in real time), and prone to errors from sighting the incorrect ruler or possibly misreading the numbers on the correct ruler.

Typically, tare readings would be taken, a 1000 lb. load would be applied, another set of readings would be taken, the load increased to 2000 lbs, with another set of readings, the load decreased to 1000 lbs to observe the hysteresis effects of the wing, and a final set of readings with no load applied. The data would then have to be manually processed, and plotted either by typing the data into a computer plotting program or manually plotting the points on graph paper. Finally, the deflected shape is compared to expected results derived from structural analysis.

II. OBJECTIVES

The objectives of this thesis are two-fold:

1. Upgrade instrumentation to state-of-the-art.

2. Improve the interactiveness of the experiment.

As discussed in the previous chapter, the manual method of measuring wing deflection by sighting two rows of metal rulers through a surveyor's theodolite was tedious, time-consuming, and prone to "eyeball error". With the availability and flexibility of computers in today's engineering world, and the accompanying reduction in time devoted to computerized data acquisition and reduction, the next logical step in the P-2V wing experiment was to computerize the deflection measurements. The computer configuration has the capability to take multiple readings from all 20 electronic displacement transducers, average these readings, which reduces errors, and store these readings in significantly less time than it takes two human operators to take and record a single reading from one metal ruler. Additionally, the computer can rapidly display the data in either tabular or graphic format, eliminating the tedious process of manually plotting all the data points once they have been optically measured and manually recorded.

Due to the previous slow method of manual data acquisition and reduction, a very limited number of points could be taken in the allotted time. Typically, the wing would be loaded to 1000 lb., increased to 2000 lb., then reduced to 1000 lb., with measurements taken for each of these loads. The second reading at 1000 lb. demonstrated the hysteresis effects present in the wing structure. There was no provision for exploring different modes of wing response to differing loads, and only a limited number of wing responses could be measured. Computerization of the data acquisition and analysis process greatly reduces the time required to fully explore the response to a given load, allowing time for exploration of other

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responses or in-depth analysis of the response to the already planned loads. The wing response to other types of loads can be readily examined due to the increased data acquisition rate. Further exploration of the hysteresis effect is possible, along with many other opportunities. Additionally, analysis of the dynamic response now becomes achievable, since data can be obtained at such a rapid rate.

III. SYSTEM IMPLEMENTATION

A. HARDWARE

The first step in eliminating the metal ruler-theodolite measuring system is to find a suitable electronic measuring device. The linear variable differential transformer (LVDT) was selected for its wide range of motion measurement, accurate conversion of displacements to velocities, and its non-contacting operating methods, minimizing perturbations during the experiment. Once the particular model of LVDT has been selected, some method of acquiring and analyzing the data must be developed. The analog output voltage of the LVDT must be converted to digital format for processing by a computer. The Labmaster card was selected for the A/D conversion and a Compuadd Standard 286-II computer analyzes and displays the data.

Model 3000DC-D LVDT's, produced by Schaevitz engineering, were selected to measure the displacements of the wing. These LVDT's measure movement through $^+/-$ 3.00 inches from the neutral position, and require only a $^+/-15$ volt input. The LVDT outputs an analog DC voltage ranging from -10 volts to +10 volts, indicating both direction and magnitude of displacement. A discussion of LVDT operating principles can be found in Appendix C. To power the LVDT's, the HP 6253A Dual DC Voltage power supply was selected.

The LVDT's were calibrated on an Instron model 4206 materials testing machine, which is capable of measuring minute movements to within 0.01mm. Positive and negative 15 volts was applied to the LVDT during calibration as required in the factory specifications. 'nput and output voltages were measured on a digital voltmeter to .0001v. Electrical and mechanical zero was determined for the LVDT, then each LVDT was moved through its entire $^+/-3.0$ inches range of motion, measuring the displacements from electrical and mechanical zero, and

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the scale factor (volts/inch) was compared to the factory value. The factory values were found to correlate to the laboratory measurements to within 1.01%. The results of these calibrations are found in Figure D.1.

After the calibration was complete, the output voltages of the LVDT's were sampled for input voltages not equal to $^+/$-15v, with a constant -40mm displacement to determine the effect of varying the input voltages. The results of this test are found in Figure 3.1. For example, with inputs of +14v and -16v,

	+13 V	+14 V	+15 V	+16 V
-13 V	-4.8893	-5.0102	-5.0817	-5.1496
-14 V	-5.0265	-5.0986	-5.1696	-5.2369
-15 V	-5.1081	-5.1809	-5.2519	-5.3179
-16 V	-5.1848	-5.2573	-5.3286	-5.3953

Figure 3.1 LVDT Voltage Test

an output voltage of -5.2573v was obtained. It had been hoped that the output voltage could be shown to be a direct function of the average magnitude of the input voltages and the displacement of the core from neutral. Based on the results demonstrated in Figure 3.1, the output voltage (V_0) is a complicated function relating all three inputs: the two input voltages (V_i^+ and V_i^-), and the displacement from neutral (δ), Eq. 1. If the input voltage is maintained within 0.5 volts of the desired 15 volts, the correction factor is assumed to be linear and is compensated for in the program by the variable VI.CORR (Eq.'s 2 and 3):

$$V_0 = f (V_i^+ , V_i^- , \delta) \qquad (1)$$

$$VI.CORR = ((V_i^+ - V_i^-) / 2) / 15 \qquad (2)$$

$$\delta_{corrected} = (\delta_{uncorrected}) * VI.CORR \qquad (3)$$

The LVDT's were mounted on a steel frame set up under the wing, with the barrel of the LVDT connected to the frame. The only attachment to the wing is a

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string tied to the connecting rod for the LVDT core. When mounting the connecting rods to the underside of the wing, several of the old aluminum tabs pulled loose from the wing. This was assumed to be due to the age of the glue, since the wing has been in place since the mid-1950's. The mounting locations and tabs were cleaned, and the tabs were reattached with epoxy adhesive in the same positions they had been mounted previously. Additional LVDT's were mounted at wing stations 437 and 502 to obtain additional data points. The LVDT mount is shown in Figure 3.2. The right angle bracket connecting the mounting
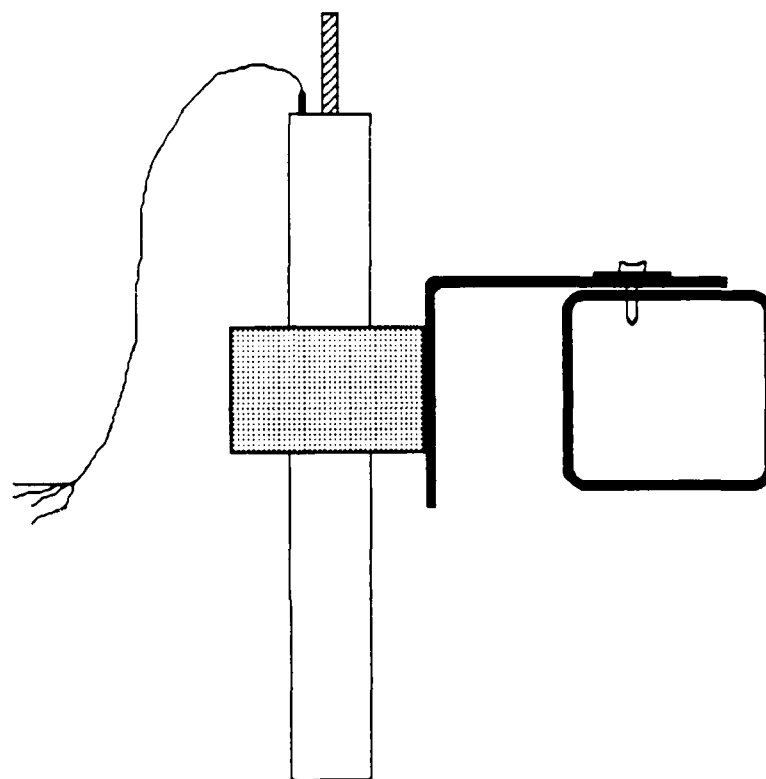
Figure 3.2 LVDT Mounting Bracket

block to the square frame is slotted to allow both lateral movement and rotation about the mounting bolt to simplify alignment problems. The support frame is

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constructed of 1/8" thick, 2" square steel tubing. The completed frame resonated audibly and visibly when disturbed. To reduce the natural resonant tendencies, the frame was loosely filled with coarse construction sand and the ends of all the tubes plugged with wood. This significantly reduced the vibrations.

The LVDT's are wired in as shown in Appendix D, Figures D.2 and D.3. The existing wiring configuration in the Labmaster ribbon cable prevented wiring the LVDT's in numerical order, and necessitated the illustrated wiring system. Every other wire in the ribbon cable, and all unused channels, is connected to ground to eliminate any cross-channel electrical interference in future dynamic tests where the signal will be oscillatory in nature (see Figures D.4 and D.5).

To display the wing deflections, a system using two banks of digital voltmeters (DVM's) was considered. However, this was discounted due to the high cost of purchasing the DVM's and the relatively slow data acquisition rate available through them. Each DVM would have cost approximately $800.00 (plus cables) and can only update its readout 100 times per second.

Anticipating the future dynamic testing of the wing, an experiment was conducted to approximate the natural frequency of the wing. The wing was configured for bending only in the negative Z-direction. Based on experimental wing deflection data(a 1522 lb force deflected the wingtip 2.21"), using Eq. 4, the stiffness of the wing is estimated to be 8264 lb/ft. Combining this with an estimate of the wing section's weight of 3000 lb. in Eq. 5, the resonant frequency is estimated to be 100 Hz.

$$k = F/d \qquad \text{spring constant ('F' in pounds, 'd' in feet)} \qquad (4)$$

$$f = 2\pi * SQRT (k / m) \qquad \text{('f' in hertz, 'm' in slugs)} \qquad (5)$$

While the DVM's would be sufficient for the static load case, they were judged inadequate for the dynamic experiment due to their relatively slow data acquisition capability. Accordingly, it was decided to process the data directly through an analog-to-digital (A/D) card which would be installed in the computer

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The A/D conversion is accomplished through the use of Labmaster data acquisition boards. The Labmaster boards provide a large variety of programming options through the use of switches on the boards and different wiring configurations. These cards are capable of acquiring data at a rate of up to 30 KHz, and each can handle up to 16 input channels, making the static deflection measurement nearly real-time. This rapid data acquisition rate and six unused channels on each card allow future expansion of the experiment. The cards are limited to an input voltage ranging from -10 to +10 volts. An input voltage outside this range will be read as the maximum value of 10.00 volts due to programming restrictions. In order to compute VI.CORR, the Labmaster board must read the two input voltages to the LVDT's, which will be approximately 15 volts. Since the Labmaster input is restricted to 10 volts, a voltage divider reduces the measured voltage to approximately 5 volts, and this voltage is then multiplied by a constant to obtain the actual input voltage.

The Labmaster cards were installed in an IBM PC-AT compatible computer, the Compuadd Standard 286-II. This computer is configured with a 80287 math co-processor for rapid computations, 44Mb hard disk drive for large storage capacity, two floppy disk drives for ease in data transfer, and a color display for an easy-to-read presentation.

B.   SOFTWARE

ASYST, a commercially available data acquisition and analysis software package, was utilized for this experiment. ASYST has a built-in computer language, and is similar in concept to "C". ASYST allows the user to tailor the system to a specific A/D card, program the number of channels being used on that card, provides a wide variety of mathematical computations to be performed on the data, and has a significant graphics capability built in. The program was configured to read data from the two Labmaster cards, each card being assigned to

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either the leading or trailing edge LVDT's. In addition to reading data from ten LVDT's, the leading edge card reads the voltages applied to the LVDT's.

Four primary functions were programmed for this system:

1. Digital voltmeter
2. Calibration
3. Deflection measurement
4. Graphic display of the deflection of both the leading and trailing edges of the wing, along with wing twist.

As soon as the program is fully loaded, the LVDT input voltages are measured by the digital voltmeter function DVM. DVM measures the voltages across the dividers, multiplies by appropriate constants, and compares to ensure the input voltages are $15.00 +/-0.1$ volts. This function is available any time the program is loaded, if the voltages require rechecking.

The calibration function CALIBRATE reads the voltage output of each of the LVDT's, converts that to a displacement based on a calibration figure for each LVDT, and stores the result for later comparison.

The deflection measurement program MEAS.DEF obtains new readings for the deflection of the wing at each LVDT once a load is placed on it and compares that to the original (calibration) value. The net displacement at each LVDT, and the twist angle (in milliradians) are displayed and printed out for each wing station. After the deflection is measured, the data can be displayed graphically if desired, through the graphic display program.

The graphic display function GRAF.DIS sets up graphic windows for, and displays the wing deflection in inches from the neutral position, and the twist along the wing, then sets up a text window alongside the graphs. Deflections for the leading and trailing edges of the wing are displayed, along with the average deflection of the wing. The average deflection is used to illustrate the coupling between torsion and bending in the wing.

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Several other routines have been programmed, but are used only in the implementation of these four primary functions, and will not be discussed in this paper.

IV. CONCLUSIONS AND RECOMMENDATIONS

This thesis has planned, designed, and implemented the capability of computerized displacement measurements in aircraft wing testing. Elimination of the tedious process of manual and optical data acquisition and plotting increases accuracy, improves operator interactiveness, and enhances in-depth analysis of the resulting measurements.

Computerization of the measurement process allows numerous options in expanding the experimental procedures. Future options include:

1. Testing the wing with distributed loads.
2. Exploring the response of different wing construction configurations.
3. Dynamic testing of the wing structural properties.
4. Incorporating the experiment into several class curricula.

Since the wing is mounted in the inverted position, distributed loads could be readily applied by simply hanging sand bags at strategic points along the wing. These sand bags would simulate the vertical load the wing would experience in flight. This distributed load would more closely approximate the inflight loading than the current single-point load being applied only at the wingtip.

There is a panel on the leading edge of the wing which could either be completely removed, or replaced by another panel to demonstrate the different structural responses. A cracked panel, or a panel constructed of composite materials would change the characteristics of the wing's performance.

With the possibility of rapid data acquisition, sufficient data can be acquired to realistically analyze the dynamic performance of the wing. The wing could be deflected by a hydraulic system with a magnetic release allowing instant release of the force, and the subsequent oscillations could be recorded and analyzed. Another alternative is to apply a steady-state oscillatory force to the wing, and

compare the resulting output oscillations to the input forces. This would also provide data concerning the resonant frequency and harmonics of the wing.

Previously, the P-2V wing experiment has been used only to demonstrate appropriate laboratory analysis and test procedures for AE2801, the Aeronautical Engineering Laboratory Introduction course. This was partly due to the limited capabilities of the experiment, requiring a large physical workload for little productive output. With the workload reduced to keyboard typing and changing the load applied to the wing, the wing experiment could readily be incorporated into several Aeronautical Engineering courses. AE3101, Flight Vehicle Structural Analysis could explore the wing performance in a variety of load applications and structural configurations. AE3340, Linear Vibration and Dynamic Stability could demonstrate the oscillatory characteristics of the wing. AE4103, Advanced Aircraft Construction could demonstrate the change in wing performance with the introduction of composite materials replacing portions of the existing all-aluminum structure.

LIST OF REFERENCES

1. Etkin, B., <u>Dynamics of Flight-Stability and Control</u> , p. 10, JohnWiley & Sons, 1982

2. Miller, J. J., <u>Automated Aircraft Static Structural Testing with Computer Aided Interpretation</u> , Master's Thesis, Naval Postgraduate School, Monterey, California, September, 1986

3. MacMillan Software Company, <u>ASYST A Scientific System</u> , version 1.56, 1985

APPENDIX A

P-2V WING DEFLECTION OPERATOR'S GUIDE

1. Complete all start-up procedures for the strain portion of the experiment, as discussed in Appendix A of LCDR Miller's thesis (1986).

2. Turn on the Compuadd computer, monitor, and printer, and the HP6253A Dual DC voltage power supply. The Compuadd computer will automatically come up on the "E" disk. The wing deflection experiment is configured to run in ASYST version 1.56. At the E> cue, ensure the ASYST 1.56 master diskette is inserted in the "A" drive (the upper floppy disk drive), turn the handle down, and type WING <cr>. This will load ASYST. In ASYST, the OK prompt indicates the program is ready for the next step in the experiment.

3. Once ASYST has completed loading, type LOAD TORSION.DOC <cr>. The loading sequence takes approximately two minutes and loads all the functions and variables required to run this experiment. As each line is loaded, a period will be displayed on the screen.

4. The final step in loading the TORSION program is to check the input voltages to the LVDT's. This is performed automatically by the function DVM (short for Digital Volt Meter). Any time during the experiment, the input voltages can be rechecked by typing DVM <cr> again.

5. Now that the program is loaded, the computer is ready to assist you in conducting the experiment. The first step in the experiment is to determine tare readings for each of the LVDT's, to compare any later deflections to. Typing CALIBRATE performs this. The CALIBRATE function measures the output voltage of each LVDT, converts the output to a displacement in inches and stores that value. CALIBRATE should be executed only once, at the beginning of the experiment. If this is typed again at some later time in the experiment, new tare readings will be set.

6. Set a torsion load on the wing and type MEAS.DEF <cr>. This reads the changed deflection at each LVDT along the wing and presents the data in tabular format, typing out Wing Station, the corresponding deflection for the Leading and Trailing edge positions (in inches), and angle of twist (in milliradians). A positive deflection indicates upward displacement, and a negative value indicates a downward displacement. A positive twist angle indicates the leading edge has moved up more than the trailing edge. All deflections and twist angles are measured from the tare position, and indicate a relative change in position. This data will be automatically printed on the dot matrix printer for reference or plotting on some other device such as Easyplot. A sample printout is included in Figure A.1 below.

Date:
09/14/87

Group: A

Time:
15:33:12

Current Load, in pounds = 1500.0

Sta	LE	TE	TWIST
573.000	.157	-.117	8.170
546.500	.112	-.092	5.694
518.500	.082	-.076	4.114
502.000	.069	-.068	3.446
486.000	.058	-.059	2.861
470.000	.051	-.053	2.467
453.000	.046	-.048	2.157
437.000	.039	-.043	1.828
420.000	.034	-.037	1.545
384.500	.026	-.030	1.137

Figure A.1 Wing Deflection Measurements

7. This same data can now be displayed graphically by typing GRAF.DIS <cr>. The upper plot will show the deflections of the leading and trailing edge positions

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(in inches) and the lower plot shows the twist angle (in milliradians) plotted against wing stations. The date, group designation, and load are displayed next to the plots and the entire screen is automatically printed. A sample print-out is shown in Figure A.2.

8. Steps 6 & 7 can be repeated for different loads as many times as desired.

9. Once the experiment is completed, be sure to secure all associated equipment.
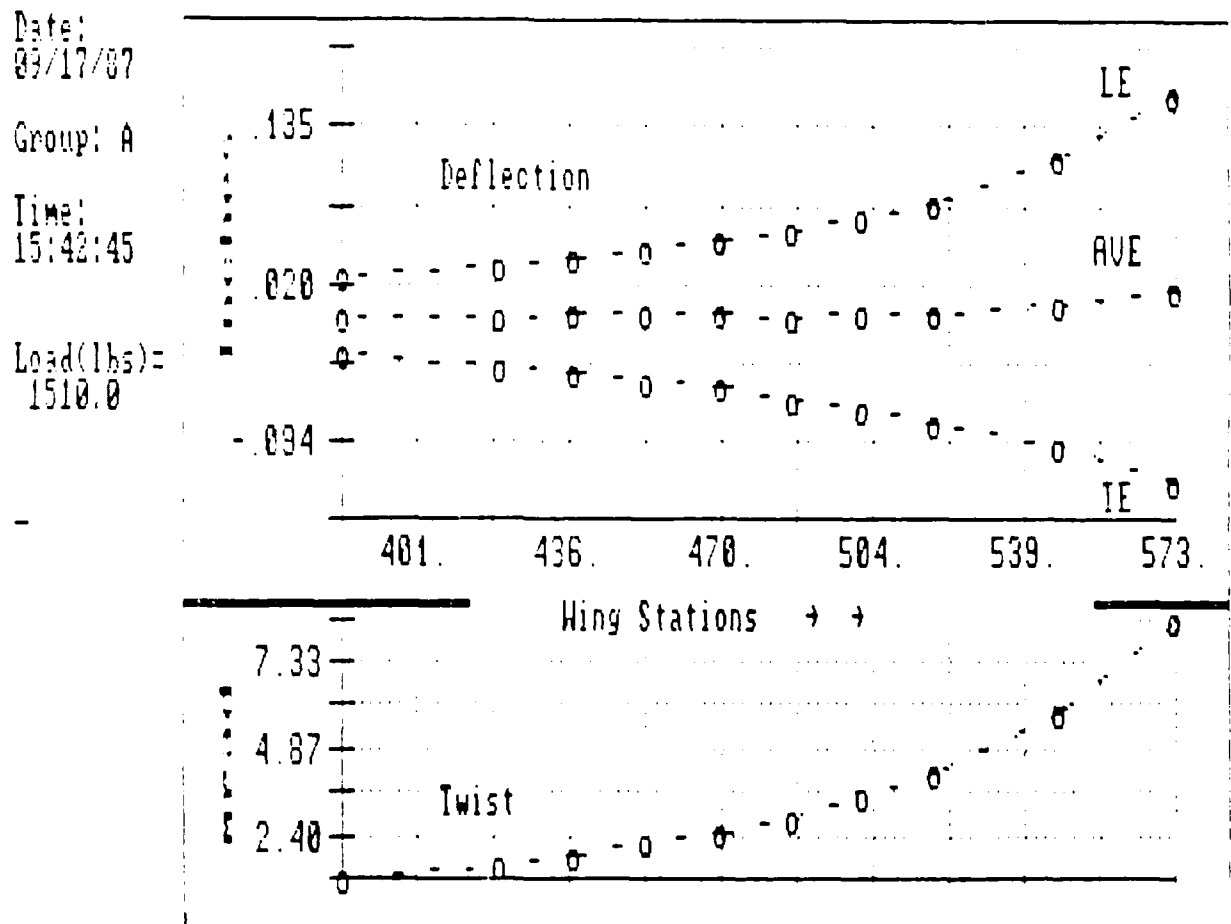
Figure A.2 Wing Deflection Plots

APPENDIX B

TORSION PROGRAM LISTING

```
echo.off
\
\ Torsion Program
\
\ Thesis Project by LCDR Joseph W. Sweeney III
\
\ Advisor :  Professor E. M. Wu
\
\ September 1987
\
." ................Welcome to the NPS P-2V wing experiment."

\
\ This program is written to work with ASYST on the
\ P-2V wing experiment for the Aeronautical Engineering
\ Department at the Naval Postgraduate School in
\ Monterey, CA.

\ Note: All variables are capitalized, while functions
\ inherent to ASYST or generated by this program are in
\ small letters.

\     Variables and definitions
\ led               template for leading edge input
\ LED.RAW           Raw inputs from Labmaster #1
\                           (Ldg edge LVDT's & Power in )
\ LED.AVE           scaled average of each column of LED.RAW
\ LEVDT.VOLTS       leading edge LVDT voltages
\ LED.CAL           calibration values for each LVDT on the
\                           leading edge
\ LED.ORIG          datum displacements
\ LED.DISPN         current wing station displacement, in inches
\ LED.C             Correction for other than +/- 15 volts LVDT
input

\ TED*              same as LED* but for trailing edge inputs

\ LED.AVE [8]       raw positive input voltage
\ POS.CAL           calibration figure for positive 15 volts
\ POS.VOLTS         input positive voltage

\ LED.AVE [7]       raw negative input voltage
\ NEG.CAL           calibration figure for negative 15 volts
\ NEG.VOLTS         input negative voltage
\ VI.BAR            Average of absolute values of input voltages
\ VI.CORR           Correction due to input voltage shift
```

```
\ GROUP           Group designation
\ DISTANCE        Distance between LE & TE for given wing
station
\ TWIST           Twist angle (mrad's) at a given wing station

-1 4   fix.format

integer dim[ 20 , 12 ] array LED.RAW
dp.real dim[ 12 ] array LED.AVE
dp.real dim[ 10 ] array LEVDT.VOLTS
dp.real dim[ 10 ] array LED.CAL
dp.real dim[ 10 ] array LED.ORIG
dp.real dim[ 10 ] array LED.DISPN
dp.real dim[ 10 ] array LED.C

dp.real scalar POS.CAL
dp.real scalar POS.VOLTS

dp.real scalar NEG.CAL
dp.real scalar NEG.VOLTS

real scalar P
real scalar N

dp.real scalar VI.BAR
dp.real scalar VI.CORR

integer dim[ 20 , 10 ] array TED.RAW
dp.real dim[ 10 ] array TED.AVE
dp.real dim[ 10 ] array TEVDT.VOLTS
dp.real dim[ 10 ] array TED.CAL
dp.real dim[ 10 ] array TED.ORIG
dp.real dim[ 10 ] array TED.DISPN
dp.real dim[ 10 ] array TED.C

dp.real dim[ 10 ] array WING.STA
dp.real dim[ 4 ] array GAR
dp.real dim[ 10 ] array DISTANCE
dp.real dim[ 10 ] array TWIST
dp.real scalar LOAD#

1 string GROUP
8 string TIM

\ input all static values
573.0 WING.STA [ 1 ] :=
546.5 WING.STA [ 2 ] :=
518.5 WING.STA [ 3 ] :=
502.0 WING.STA [ 4 ] :=
486.0 WING.STA [ 5 ] :=
470.0 WING.STA [ 6 ] :=
```

```
453.0 WING.STA [ 7 ] :=
437.0 WING.STA [ 8 ] :=
420.0 WING.STA [ 9 ] :=
384.5 WING.STA [ 10 ] :=

\ Distance from LE to TE LVDT's
33.50 DISTANCE [ 1 ] :=
35.83 DISTANCE [ 2 ] :=
38.31 DISTANCE [ 3 ] :=
39.58 DISTANCE [ 4 ] :=
41.08 DISTANCE [ 5 ] :=
42.52 DISTANCE [ 6 ] :=
43.62 DISTANCE [ 7 ] :=
45.02 DISTANCE [ 8 ] :=
46.35 DISTANCE [ 9 ] :=
49.24 DISTANCE [ 10 ] :=


\ Correction values for off-15 volt inputs
1. LED.C [ 1 ] :=
1. LED.C [ 2 ] :=
1. LED.C [ 3 ] :=
1. LED.C [ 4 ] :=
1. LED.C [ 5 ] :=
1. LED.C [ 6 ] :=
1. LED.C [ 7 ] :=
1. LED.C [ 8 ] :=
1. LED.C [ 9 ] :=
1. LED.C [ 10 ] :=


." Programmed by LCDR J.W. Sweeney III, Sep 1987"
1. TED.C [ 1 ] :=
1. TED.C [ 2 ] :=
1. TED.C [ 3 ] :=
1. TED.C [ 4 ] :=
1. TED.C [ 5 ] :=
1. TED.C [ 6 ] :=
1. TED.C [ 7 ] :=
1. TED.C [ 8 ] :=
1. TED.C [ 9 ] :=
1. TED.C [ 10 ] :=

\ Calibration values determined 15-17 Jul 87 in NPS
Composites
\ Lab by Jim Nageotte & Joe Sweeney III on Instron Equipment

\ cal value                 LVDT#        wing sta/ L or T

3.3980  LED.CAL [ 10 ] := \ 970          L 384.5
3.4247  LED.CAL [ 9 ] :=  \ 974          L 420.0
```

```
3.2687   LED.CAL [ 8 ] :=  \  988          L 437.0
3.3846   LED.CAL [ 7 ] :=  \  989          L 453.0
3.3462   LED.CAL [ 6 ] :=  \  992          L 470.0
3.2914   LED.CAL [ 5 ] :=  \ 1000          L 486.0
3.3569   LED.CAL [ 4 ] :=  \ 1001          L 502.0
3.4300   LED.CAL [ 3 ] :=  \ 1010          L 518.5
3.2813   LED.CAL [ 2 ] :=  \ 1012          L 546.5
3.3806   LED.CAL [ 1 ] :=  \ 1062          L 573.0

3.2760   TED.CAL [ 10 ] := \ 1049          T 384.5
3.2991   TED.CAL [ 9 ] :=  \ 1050          T 420.0
3.4080   TED.CAL [ 8 ] :=  \ 1051          T 437.0
3.2956   TED.CAL [ 7 ] :=  \ 1052          T 453.0
3.3038   TED.CAL [ 6 ] :=  \ 1054          T 470.0
3.3107   TED.CAL [ 5 ] :=  \ 1055          T 486.0
3.3405   TED.CAL [ 4 ] :=  \ 1056          T 502.0
3.3607   TED.CAL [ 3 ] :=  \ 1058          T 518.5
3.3722   TED.CAL [ 2 ] :=  \ 1059          T 546.5
3.4045   TED.CAL [ 1 ] :=  \ 1060          T 573.0

2.96524 NEG.CAL :=
3.03264 POS.CAL :=

1 board                              \ set up template
0 11 a/d.template led                \ for ldg edge
20 template.repeat
LED.RAW template.buffer


2 board                              \ set up template
0 9 a/d.template ted                 \ for trlg edge
20 template.repeat
TED.RAW template.buffer


: get.disp
        led                                       \ set
template,
        a/d.init                                  \ read data
for
        a/d.in>array                              \ leading
edge
        LED.RAW xsect[ 1 , ! ]
        21 2 do
         LED.RAW xsect[ i , ! ] +
        loop
        20. / -10. 10. a/d.scale LED.AVE :=

\ set raw voltage readings to proper scale
        LED.AVE [ 7 ] NEG.CAL * NEG.VOLTS :=
```

```
            LED.AVE [ 8 ] POS.CAL * POS.VOLTS :=

            POS.VOLTS NEG.VOLTS - 2. / VI.BAR :=
            VI.BAR 15. / VI.CORR :=


    \ now correlate channel readings to respective wing sta
    LVDT's
            LED.AVE [ 1 ] LEVDT.VOLTS [ 1 ] :=
            LED.AVE [ 2 ] LEVDT.VOLTS [ 3 ] :=
            LED.AVE [ 3 ] LEVDT.VOLTS [ 5 ] :=
            LED.AVE [ 4 ] LEVDT.VOLTS [ 7 ] :=
            LED.AVE [ 5 ] LEVDT.VOLTS [ 9 ] :=
            LED.AVE [ 6 ] LEVDT.VOLTS [ 10 ] :=
            LED.AVE [ 9 ] LEVDT.VOLTS [ 2 ] :=
            LED.AVE [ 10 ] LEVDT.VOLTS [ 4 ] :=
            LED.AVE [ 11 ] LEVDT.VOLTS [ 6 ] :=
            LED.AVE [ 12 ] LEVDT.VOLTS [ 8 ] :=
    \ Correct for "off-voltages" on input
            LEVDT.VOLTS VI.CORR * LEVDT.VOLTS :=

            ted                                            \ set
    template,
            a/d.init                                       \ read data
    for
            a/d.in>array                                   \ trailing
    edge
            TED.RAW xsect[ 1 , ! ]
            21 2 do
              TED.RAW xsect[ I , ! ] +
            loop
            20. / -10. 10. a/d.scale TED.AVE :=

    \ now correlate channel readings to respective wing sta
    LVDT's
            TED.AVE [ 1 ] TEVDT.VOLTS [ 1 ] :=
            TED.AVE [ 2 ] TEVDT.VOLTS [ 3 ] :=
            TED.AVE [ 3 ] TEVDT.VOLTS [ 5 ] :=
            TED.AVE [ 4 ] TEVDT.VOLTS [ 7 ] :=
            TED.AVE [ 5 ] TEVDT.VOLTS [ 9 ] :=
            TED.AVE [ 6 ] TEVDT.VOLTS [ 6 ] :=
            TED.AVE [ 7 ] TEVDT.VOLTS [ 8 ] :=
            TED.AVE [ 8 ] TEVDT.VOLTS [ 10 ] :=
            TED.AVE [ 9 ] TEVDT.VOLTS [ 2 ] :=
            TED.AVE [ 10 ] TEVDT.VOLTS [ 4 ] :=
    \ Correct for "off-voltages" on inputs
            TEVDT.VOLTS VI.CORR * TEVDT.VOLTS :=
    ;
    ." Please stand by while I finish loading the program"
    \ Check the LVDT power supply to ensure +/-15 volts
    : dvm
```

```
            0. P :=
            0. N :=
            begin
                screen.clear
                get.disp
                cr ." Testing LVDT Power Supply  " cr
                P N + 1.9 <
         while
                pos.volts .
                pos.volts 15.100 >
                if
                   cr ." Positive voltage too high.   Decrease
   # Volts."
                   bell
                else
                   pos.volts 14.900 <
                      if
                         cr ." Positive voltage too low.
   Increase # Volts."
                         bell
                      else
                         cr ." Positive voltage within limits."
                         1. P :=
                      then
                then cr cr
                neg.volts .
                neg.volts -15.1000 <
                if
                   cr ." Negative voltage too large.
   Decrease # volts."
                   bell
                else
                   neg.volts -14.9000 >
                   if
                      cr ." Negative voltage too small.
   Increase # volts."
                      bell
                   else
                      cr ." Negative voltage within limits."
                      1. N :=
                   then
                   1000 1 do
                   loop  \ time delay
                then
         repeat
         cr POS.VOLTS . ." = Positive input"
         cr NEG.VOLTS . ." = Negative input" cr
         cr ." Both voltages within limits. Proceed with
   Calibrate function. "
   ;
```

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```
\ Set up view port for displacements picture
  :  top.pic
        .145  .350 vuport.orig
        .855  .645 vuport.size
        horizontal axis.fit.off grid.on
        vertical   axis.fit.off grid.on
  ;


\ Set up window for wing twist
  : bot.pic
        .145   .000 vuport.orig
        .855   .357 vuport.size
  ;


\ Set up side window for text
0 0 24 9 window (side)
\ Set up middle window for label
16 30 16 70 window (middle)


\ Display group data
  : group.data
        "time TIM ":=
        ." Date: " cr "date "type cr cr
        ." Group: " GROUP "type cr cr
        ." Time: " cr TIM "type cr
  ;


\ Graphically display the data
: graf.dis
        screen.clear
        stack.clear
        graphics.display
        top.pic
                vuport.clear
                384. 573. horizontal world.set
                TED.DISPN [ 1 ] 1.2 * LED.DISPN [ 1 ] 1.2 *
vertical world.set
                11 6 axis.divisions
                1 2 horizontal label.points
                xy.axis.plot
                outline
                .01 .02 .01 .02 " o" dashed&symbol
                WING.STA LED.DISPN xy.data.plot
                world.coords
                560. LED.DISPN [ 1 ] 1.06 * position
                        " LE" centered.label
                WING.STA TED.DISPN xy.data.plot
                560. TED.DISPN [ 1 ] 1.06 * position
                        " TE" centered.label
                WING.STA LED.DISPN TED.DISPN + 2. /
xy.data.plot
```

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```
                        560. TED.DISPN [ 1 ] LED.DISPN [ 1 ] + .75 /
        position
                        " AVE" centered.label
                        normal.coords
                        .03 .5 position
                        90 label.dir
                        90 char.dir
                        " Inches" centered.label
            bot.pic
                        TWIST [ 10 ] TWIST [ 1 ] vertical world.set
                        horizontal no.labels
                        0 label.dir
                        0 char.dir
                        xy.axis.plot
                        .01 .02 .01 .02 " o" dashed&symbol
                        WING.STA TWIST xy.data.plot
                        outline
                          normal.coords
                          .03 .40 position
                          90 label.dir
                          90 char.dir
                          " Twist" centered.label
                          0.   0. position
            {middle}
              screen.clear
              ."          Wing Stations" 3 spaces 26 emit 2 spaces
        26 emit
            {side}
            screen.clear
            group.data cr cr
            -1 1 fix.format
            ." Load(lbs)=" cr LOAD# . cr cr cr
            -1 4 fix.format
            screen.print
        ;


        \ Display the results in tabular format:
        : disp.res
              -1 3 fix.format
              group.data
              cr ." Current load, in pounds = " LOAD# . cr cr
              ."    Sta        LE       TE      TWIST "
          11 1 do
              WING.STA [ I ] GAR [ 1 ] :=
              LED.DISPN [ I ] GAR [ 2 ] :=
              TED.DISPN [ I ] GAR [ 3 ] :=
              TWIST [ I ] GAR [ 4 ] :=
              GAR .
          loop
              cr cr screen.print
```

```
                    -1 4 fix.format
        ;




        \ Calibration Phase

        : calibrate
                cr
                ." Please input your group: A, B, or C ?" cr
                "input GROUP ":=

                get.disp
                LEVDT.VOLTS LED.CAL / LED.ORIG :=
                TEVDT.VOLTS TED.CAL / TED.ORIG :=

                cr
                ." The P-2V wing is now calibrated and ready for the
        experiment."

        ;



        \ Measure the deflection for a given load
        \
        : meas.def
                normal.display
                cr ." Input current wing loading ( in pounds ): " cr
                #input  LOAD# :=
                screen.clear
                get.disp

                LEVDT.VOLTS LED.CAL /
                LED.ORIG - LED.DISPN :=

                TEVDT.VOLTS TED.CAL /
                TED.ORIG - TED.DISPN :=

                rad
                LED.DISPN TED.DISPN - DISTANCE / atan 1000. * TWIST
        :=
                disp.res
        ;


dvm
cr cr
." ......Ready when you are......."
cr
```

APPENDIX C

LVDT OPERATIONS

The LVDT operates on the principle of an AC transformer with a constant excitation voltage applied to the input coils. A movable ferris core is physically attached to the displacement point, the movement of which changes its relative position between the input and output coils, changing the electro-magnetic coupling, and hence the output voltage. The output voltage is used to measure the displacement of the core. The basic circuitry of the LVDT is shown in Figure C.1. The input DC excitation voltage (+15 and -15 volts) is converted to an AC voltage at 2.5 KHz. The high frequency facilitates the measurement of dynamic displacements. Typically, satisfactory measurement of dynamic displacements can be made with frequencies up to $1/\omega$ of the carrier frequency of the input signal.
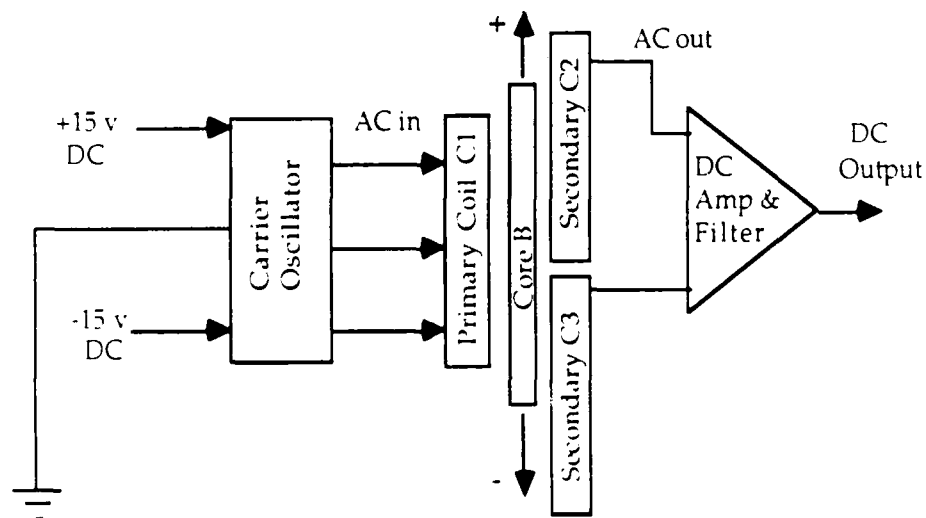

Figure C.1 LVDT Circuitry Diagram

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As shown in, this AC input signal excites the primary coil C1. The displacement core B provides electromagnetic coupling to the secondary coils C2 and C3. Displacement of the core in the positive direction will increase the coupling between C1 and C2, and decrease the coupling between C1 and C3, creating a positive voltage difference across the two secondary coils. The magnitude of the voltage is determined by the movement of the core, and the polarity is determined by the direction of movement. This difference in AC voltage is then converted back to a DC signal as the output of the LVDT.

The DC signal is converted to a displacement by software in the computer for further analysis.

APPENDIX D

CALIBRATION DATA AND FIGURES

LVDT #	Lab. Volts/In	Factory V/In	Lab/Factory(%)
970	3.3980	3.424	99.24
974	3.4247	3.442	99.50
988	3.2687	3.286	99.47
989	3.3846	3.419	98.99
992	3.3462	3.358	99.65
1000	3.2914	3.296	99.86
1001	3.3569	3.365	99.76
1010	3.4300	3.441	99.68
1012	3.2813	3.292	99.67
1048	3.3296	3.341	99.66
1049	3.2760	3.286	99.70
1050	3.2991	3.316	99.41
1051	3.4080	3.422	99.59
1052	3.2956	3.311	99.53
1054	3.3038	3.317	99.60
1055	3.3107	3.308	100.08
1056	3.3405	3.352	99.66
1058	3.3607	3.379	99.46
1059	3.3722	3.382	99.71
1060	3.4045	3.420	99.55
1062	3.3806	3.405	99.28

Figure D.1 Calibration Comparisons

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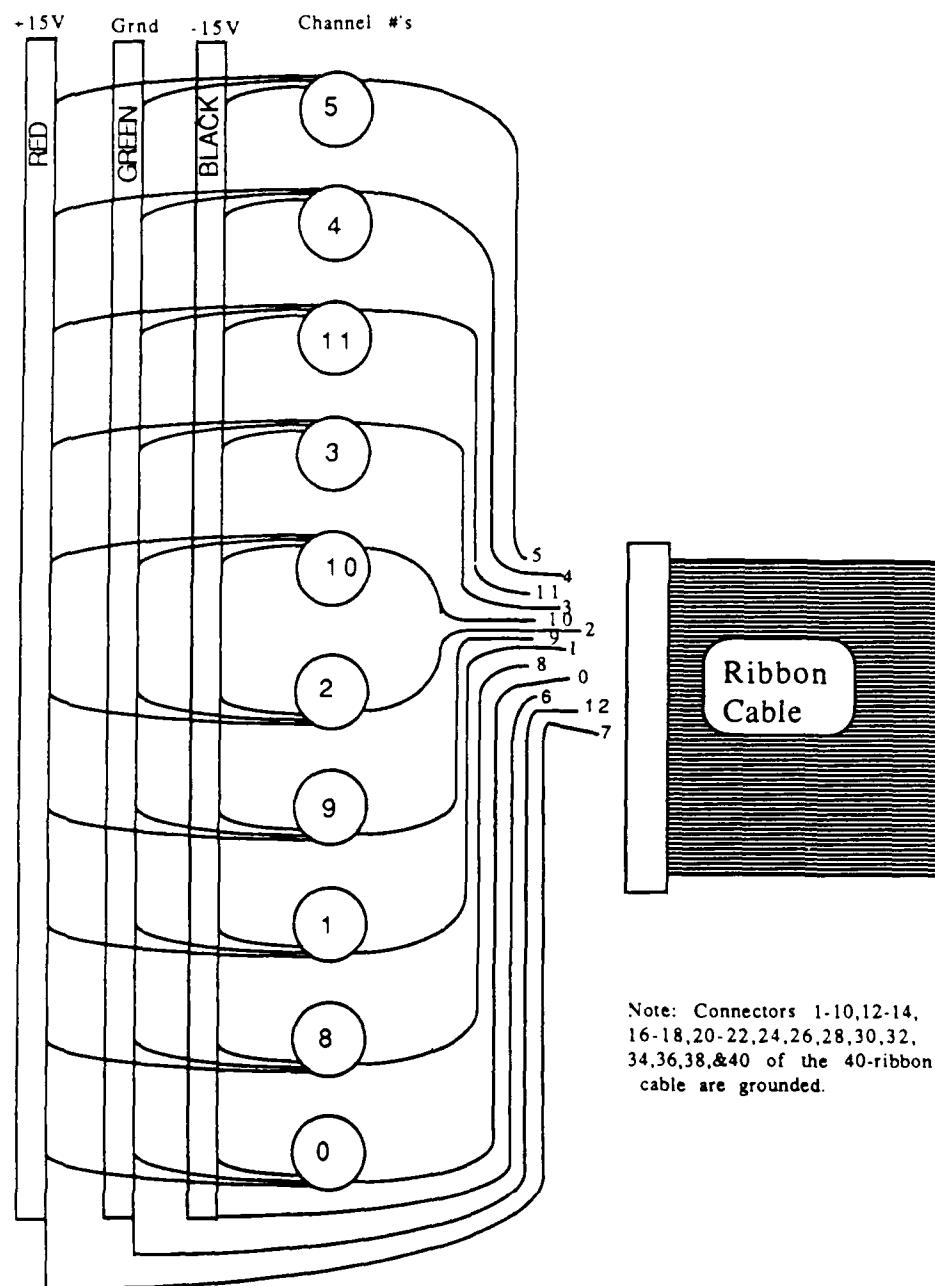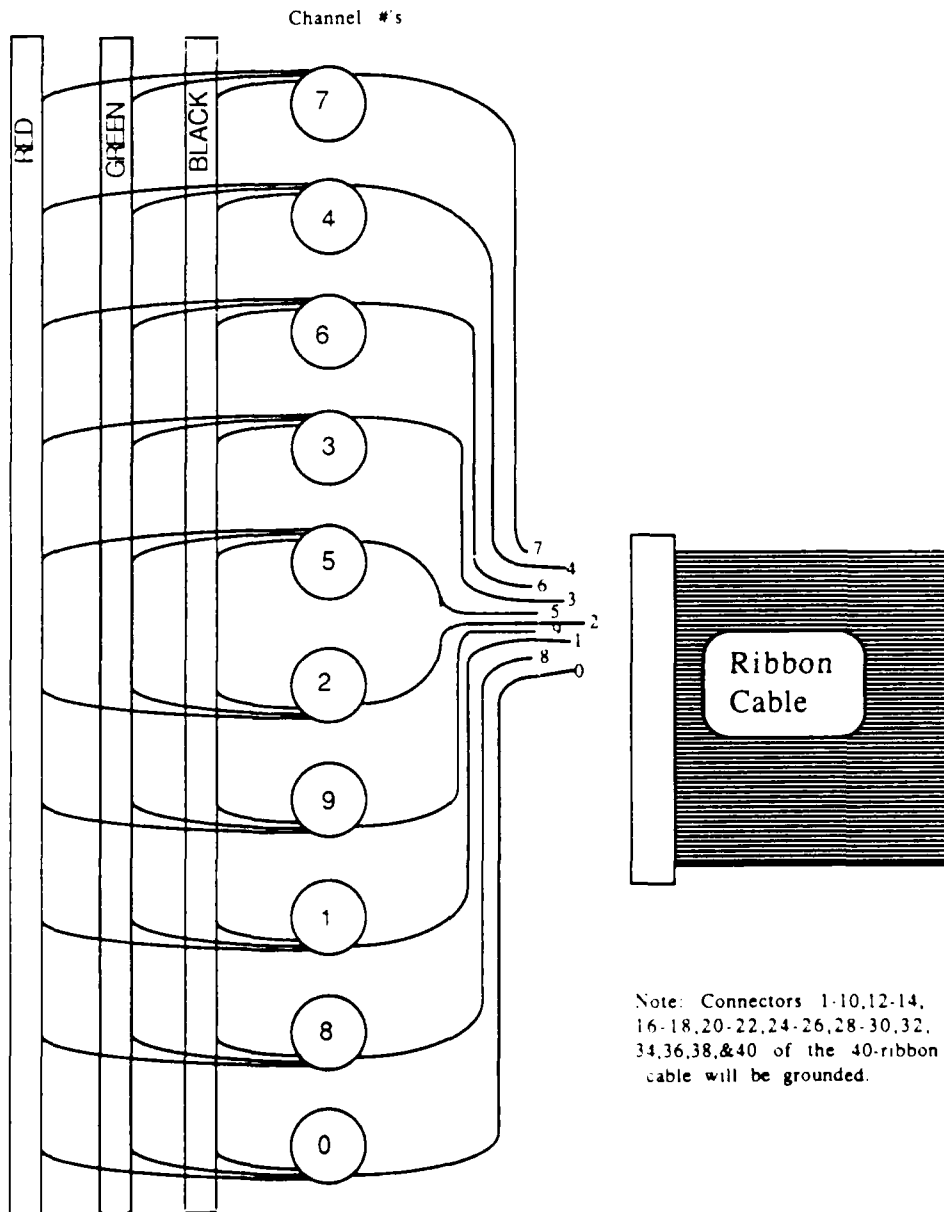
Figure D.2 Leading Edge LVDT Wiring Diagram

Channel #'s

Note: Connectors 1-10,12-14,
16-18,20-22,24-26,28-30,32,
34,36,38,&40 of the 40-ribbon
cable will be grounded.

Figure D.3 Trailing Edge LVDT Wiring Diagram

Wire#	Pin#	Channel#
1	1	Grnd
2	21	Grnd
3	2	Grnd
4	22	Grnd
5	3	Grnd
6	23	Grnd
7	4	Grnd
8	24	Grnd
9	5	15 /Grnd'd
10	25	Grnd
11	6	7/ +15V
12	26	Grnd
13	7	14 /Grnd'd
14	27	Grnd
15	8	6/ -15V
16	28	Grnd
17	9	13 /Grnd'd
18	29	Grnd
19	10	5/ LVDT
20	30	Grnd
21	11	12 /Grnd'd
22	31	Grnd
23	12	4/ LVDT
24	32	Grnd
25	13	11/ LVDT
26	33	Grnd
27	14	3/ LVDT
28	34	Grnd
29	15	10/ LVDT
30	35	Grnd
31	16	2/ LVDT
32	36	Grnd
33	17	9/ LVDT
34	37	Grnd
35	18	1/ LVDT
36	38	Grnd
37	19	8/ LVDT
38	39	Grnd
39	20	0/ LVDT
40	40	Grnd

Figure D.4 Leading Edge Ribbon Cable Layout

Wire#	Pin#	Channel#
1	1	Grnd
2	21	Grnd
3	2	Grnd
4	22	Grnd
5	3	Grnd
6	23	Grnd
7	4	Grnd
8	24	Grnd
9	5	15/ Grnd
10	25	Grnd
11	6	7/ LVDT
12	26	Grnd
13	7	14/ Grnd
14	27	Grnd
15	8	6/ LVDT
16	28	Grnd
17	9	13/ Grnd
18	29	Grnd
19	10	5/ LVDT
20	30	Grnd
21	11	12/ Grnd
22	31	Grnd
23	12	4 / LVDT
24	32	Grnd
25	13	11/ Grnd
26	33	Grnd
27	14	3 / LVDT
28	34	Grnd
29	15	10/ Grnd
30	35	Grnd
31	16	2 / LVDT
32	36	Grnd
33	17	9 / LVDT
34	37	Grnd
35	18	1 / LVDT
36	38	Grnd
37	19	8 / LVDT
38	39	Grnd
39	20	0 / LVDT
40	40	Grnd

Figure D.5 Trailing Edge Ribbon Cable Layout

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